VENTAIR
Version 2.1

User's Manual

November 1982

Assistance and Information:

K. Ford
Design Aids Engineer
Solar Programs Office
Sir Charles Tupper Building
Riverside Drive
Ottawa K1A 0M2

(613) 998-3641

This document is not a departmental publication.
Do not cite as a reference or catalogue in a library.

User Responsibility

Users are responsible for the validity of the information generated by VENTAIR, Version 2.1. Consequently the program should not be used by those who do not comprehend the technical field to which this program applies. Neither Public Works Canada nor any person acting on behalf of the department makes any warrenty or assumes any responsibility for accuracy, completeness or usefulness of any information generated by this program.

TABLE OF CONTENTS

	Page
1. INTRODUCTION	1
1.1 Introduction to Ventilation Air Systems	1
1.2 Introduction to Industrial Process Air Heating Systems	2
2. THE VENTAIR-2 COMPUTER PROGRAM	3
2.1 System Configuration	3
2.2 System Operating Strategy	3
2.3 Tutorial Session	6
3. SYSTEM INPUT PARAMETERS	15
3.1 Definition of Input Parameters	15
3.2 Weather Data and Map	18
4. DESCRIPTION OF PROGRAM OUTPUT	22
5. PROGRAM ALGORITHM	24
5.1 Overview of Program Operation	24
5.2 Algorithm for the Calculation of F_R	25
5.3 Algorithm to Process Weather Data	32
6. PROGRAM STRUCTURE	36
7. REFERENCES	38
8. INPUT DATA WORK SHEET	39
9. NOMENCLATURE	40
FIGURE 1: SYSTEM SCHEMATIC	4
FIGURE 2: VENTAIR-2 PROGRAM FLOW CHART	26,27
FIGURE 3: SCHEMATIC OF FIBRE MATRIX SOLAR COLLECTOR	30
FIGURE 4: VENTAIR-2 PROGRAM STRUCTURE	37

1. INTRODUCTION

The VENTAIR-2 computer program was developed by Enermodal Engineering Limited to simulate the performance of air-based solar collectors used in the preheating of industrial process or building ventilation air. The program can accept data of all PUSH approved air-based collectors (Amherst 200, Solartech Solair, and Watershed A100) and any other parallel plate air-based collector.

VENTAIR-2 is the only computer program capable of simulating solar preheating of process or ventilation air. Performance calculations use a one-hour time step to ensure maximum accuracy. An important restriction, however, on the use of the program is that the air demand must be constant over the hour. A system not applicable to the VENTAIR-2 program, for example, is a bathroom ventilation system operating by a light switch or short duration timer.

The VENTAIR-2 computer program will provide an accurate estimate of thermal performance of solar preheated process or ventilation air systems provided that the user supplies system parameters within the program limitations. All users should read and understand this manual before using the program.

1.1 Introduction to Ventilation Air Systems

In many buildings a high rate of change of ventilation air is necessary for the health of the occupants or proper operating of equipment. Such buildings include hospitals, vehicle maintenance garages, indoor swimming pools and commercial kitchens. The volumes of air involved are often quite large (6 air changes/hour) and correspondingly large quantities of energy are required to raise the air temperature to the building temperature. This air is normally heated by steam coils or electric resistance heaters.

To reduce energy consumption, heat recovery equipment can be used to transfer some of the heat from the exhaust air to the fresh air. Heat recovery equipment, however, has several limitations. The equipment suffers from frost build-up in sub-freezing conditions, fouling from kitchen grease, and requires modifications if the exhaust air contains toxic chemicals. The installation of this equipment can be expensive in retrofit situations if return air duct work must be added.

Use of air-based solar collectors to preheat ventilation air has been proposed as a parallel application of a viable alternative to heat recovery equipment in many applications. In making a decision to use this type of system, it is necessary to estimate the yearly thermal performance. The VENTAIR-2 computer program was designed specifically to assist the designer in evaluating the system performance of solar preheated ventilation air systems.

1.2 Introduction to Industrial Process Air Heating Systems

Many industrial processes require large volumes of air for drying and/or heating. Such processes include paint drying, food drying, combustion air preheating and sterilization/drying of bottles and cans. The VENTAIR-2 computer program can also be used to simulate solar preheating of these processes provided that the air flow rate is constant over each hour. If the flow rate is dependent on the relative humidity and/or ambient temperature the VENTAIR-2 computer program is not suitable.

2. THE VENTAIR-2 COMPUTER PROGRAM

2.1 System Configuration

In a conventional make-up air unit, fresh (outside) air is taken into the building by a roof top fan. A bypass damper automatically adjusts the fraction of the intake air that passes through the heating coil to maintain the required inlet air temperature. Exhaust air is expelled to the outdoors by a separate system.

Figure 1 shows a system schematic for a typical solar preheated process or ventilation air system. This system differs from conventional solar space heating systems in two important areas. First, the inlet air to the collector is the outside or ambient air, as opposed to the building air. This means that the collector will operate at a lower temperature and a higher efficiency. Second, because the solar energy is delivered immediately to the heating load there is no need for thermal storage. If the solar heating contribution of the total heating load is below 35%, this system can deliver more energy per square metre than a conventional solar space heating system (see reference 1). If a solar contribution significantly higher than 35% is required, thermal storage should be considered, although the increased cost may not be justified. A side effect of eliminating the storage unit is the simplification of system control and ductwork.

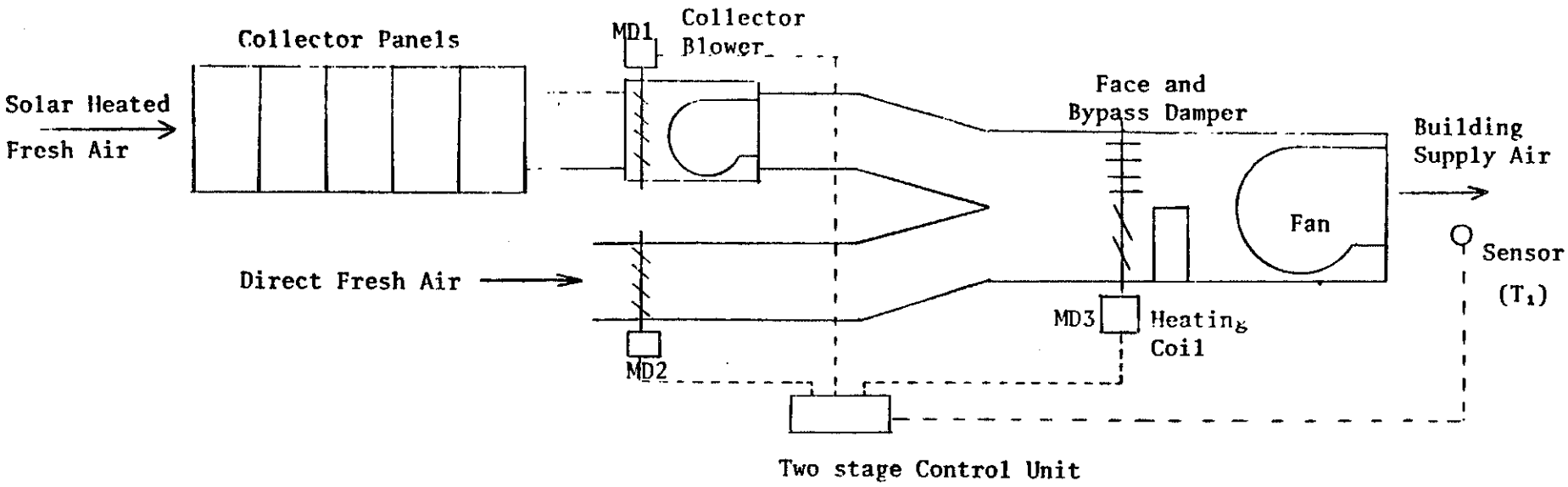
2.2 System Operating Strategy

The system has three modes of operation (excluding complete shut down). These modes are summarized in Figure 1 and described below.

(1) No Solar Heating

If the ambient air temperature is greater than the required building

Fig.1 System Schematic



T_{bg} is the desired inlet temperature to the building or process

Sequence of Operation							
Stage	Tamb	Damper 1 (MD1)	Damper 2 (MD2)	Collector Blower	MD3	Heating Coil	T_1
1	> T_{bg}	C	O	OFF	bypass	OFF	T_{bg}
2	< T_{bg}	O	O	ON	bypass	OFF	T_{bg}
3	< Tbg	O	C	ON	bypass and coil	ON	T_{bg}

or process air temperature, no heating of the air is required. In order to eliminate an unnecessarily high cooling load, all air enters the direct fresh air intake bypassing the solar collectors. The air bypasses the heating coil and is handled by conventional air conditioning equipment before entering the space.

(2) All Solar Heating

If the ambient air temperature drops below the building or process temperature, some air would flow through the collectors. This is accomplished by partially opening damper 1 and partially closing damper 2 (see Figure 1). Flow would continue to be diverted until the supply air temperature reaches the building or process temperature. In this operation all the heat necessary to bring the ambient air temperature up to the building or process temperature is supplied by the solar collectors.

(3) Partial Solar Heating

As the ambient temperature continues to decrease, more air is taken through the collectors and less through the direct fresh air intake. A point will be reached when the collectors are operating at maximum air flow (damper 1 fully open, damper 2 fully closed) and the building supply air temperature (T1) is less than the required temperature. In this case, additional heating is supplied by the heating coil.

It should be noted that solar collectors have a maximum flow rate where the incremental solar heat gain is less than the incremental fan energy

consumption. Thus in many designs, with the maximum flow rate of air flowing through the collectors, some air would be supplied through the direct fresh air intake in order to meet the required ventilation rate.

In Mode 2 all the available solar heat has not been used. Theoretically, this heat could be used to heat the building (i.e. by supplying ventilation air at a temperature higher than the building temperature). However, this is a much more difficult control problem requiring zone heat control for ventilated and unventilated areas. Control feedback to the solar ventilation system would be necessary in the ventilated areas to prevent overheating. Such a control strategy is not considered applicable for space heating.

2.3 Tutorial Session

This section describes how to use the VENTAIR-2 computer program. A full description of the input parameters is given in Section 3, and program output in Section 4.

When you have successfully signed on to your account and accessed the program, the computer will respond with the header.

```
**************************************************************

                    *** VENTAIR - 2.1 ***

  AN HOUR-BY-HOUR COMPUTER PROGRAM TO MODEL USE OF SOLAR
     COLLECTORS TO PREHEAT BUILDING VENTILATION AIR

**************************************************************
```

The program will prompt the user for values of input parameters for four sections: solar radiation, collector, systems, and ventilation rate schedule as follows.

```
*** SOLAR RADIATION SECTION ***

ENTER COLLECTOR SLOPE (DEG.)
45.
ENTER COLLECTOR AZIMUTH ANGLE - SOUTH=0  (DEG)
0.0
ENTER LOCATION LATITUDE  (DEG)
45.
  PROCESSING WEATHER DATA, PLEASE BE PATIENT...

*** COLLECTOR SECTION ***
 THE PROGRAM HAS DATA FOR 4 SOLAR COLLECTORS :
      1 - AMHERST 200
      2 - SOLARTECH SOLAIR
      3 - WATERSHED A100 (NARROW CHANNEL)
      4 - WATERSHED A100 (WIDE CHANNEL)

  SELECT THE COLLECTOR TO BE SIMULATED
  (USE ZERO FOR A COLLECTOR NOT LISTED ABOVE, HOWEVER IT MUST BE
     A PARALLEL PLATE COLLECTOR, NOT A FIBRE MATRIX COLLECTOR)
3

*** SYSTEMS SECTION ***

ENTER REQUIRED BUILDING OR PROCESS TEMPERATURE  (C)
20.
ENTER GROSS COLLECTOR AREA  (M**2)
100.
ENTER MAXIMUM ALLOWABLE SOLAR SYSTEM FLOW RATE  (M**3/S)
1.5
ENTER ARRAY FLOW PATH LENGTH (M)①
10.

*** VENTILATION RATE SCHEDULE SECTION ***

ENTER LOAD SCHEDULE TYPE....
1 - CONSTANT VENTILATION RATE
2 - TWO VENTILATION RATES PER DAY
3 - VENTILATION RATE DIFFERENT FOR EACH HOUR
1

ENTER BUILDING VENTILATION RATE  (M**3/S)
3.0
```

① see page 18 for description

When all of the input data has been entered, the user is able to modify any of the sections. The program will prompt the user with questions; to respond type Y for yes and N for no.

```
DO YOU WISH TO CONTINUE ? (Y/N)
Y
ARE ALL THE VALUES CORRECT ? (Y/N)
Y
```

If the user types N in response to "DO YOU WISH TO CONTINUE" the program will stop and the session will be over. If the user answers N to "ARE ALL THE VALUES CORRECT?", the program will ask which section(s) are to be modified. If the solar radiation section is changed the weather data will be reprocessed.

```
DO YOU WISH TO CHANGE SOLAR RADIATION SECTION ? (Y/N)
n
DO YOU WISH TO CHANGE COLLECTOR SECTION ? (Y/N)
n
DO YOU WISH TO CHANGE SYSTEMS SECTION ? (Y/N)
n
DO YOU WISH TO CHANGE VENTILATION RATE SCHEDULE SECTION ? (Y/N)
n
```

When all input values are correct, the program will ask for the title of the run. The title has no effect on the program calculations, but merely serves as a method for distinguishing between computer runs.

The title can be up to 64 characters in length (including blanks) on a single line.

```
ENTER TITLE OF RUN
   sample run
```

After the title has been entered, the simulation starts. The program first prints out the input data and the run title.

****

VENTAIR - 2.1
SOLAR PREHEATED VENTILATION AIR PROGRAM
TO MODEL USE OF SOLAR COLLECTORS TO PREHEAT VENTILATION AIR

****

SAMPLE RUN

INPUT DATA

SOLAR RADIATION DATA

COLLECTOR SLOPE (DEG)	45.00
COLLECTOR AZIMUTH (DEG)	0.00
LOCATION LATITUDE (DEG)	45.00

COLLECTOR TEST DATA

FRTA	0.580
FRUL (W/M2/C)	2.710
COLLECTOR TRANS-ABSORP PRODUCT	0.860
APERATURE TO GROSS AREA RATIO	0.872
COLLECTOR TEST FLOW RATE (M3/S/M2)	0.010
CHANNEL HEIGHT (M)	0.025
FLOW LENGTH (TEST CONDITIONS) (M)	10.000

SYSTEMS DATA

GROSS COLLECTOR AREA (M2)	100.0
MAXIMUM SOLAR SYSTEM FLOW RATE (M3/S)	1.50
BUILDING OR PROCESS TEMPERATURE (C)	20.00
ARRAY FLOW LENGTH (M)	10.00

VENTILATION RATE SCHEDULE (M3/S)
DAY OF THE WEEK

HOUR	1	2	3	4	5	6	7
0	3.00	3.00	3.00	3.00	3.00	3.00	3.00
1	3.00	3.00	3.00	3.00	3.00	3.00	3.00
2	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3	3.00	3.00	3.00	3.00	3.00	3.00	3.00
4	3.00	3.00	3.00	3.00	3.00	3.00	3.00
5	3.00	3.00	3.00	3.00	3.00	3.00	3.00
6	3.00	3.00	3.00	3.00	3.00	3.00	3.00
7	3.00	3.00	3.00	3.00	3.00	3.00	3.00
8	3.00	3.00	3.00	3.00	3.00	3.00	3.00
9	3.00	3.00	3.00	3.00	3.00	3.00	3.00

10	3.00	3.00	3.00	3.00	3.00	3.00	3.00
11	3.00	3.00	3.00	3.00	3.00	3.00	3.00
12	3.00	3.00	3.00	3.00	3.00	3.00	3.00
13	3.00	3.00	3.00	3.00	3.00	3.00	3.00
14	3.00	3.00	3.00	3.00	3.00	3.00	3.00
15	3.00	3.00	3.00	3.00	3.00	3.00	3.00
16	3.00	3.00	3.00	3.00	3.00	3.00	3.00
17	3.00	3.00	3.00	3.00	3.00	3.00	3.00
18	3.00	3.00	3.00	3.00	3.00	3.00	3.00
19	3.00	3.00	3.00	3.00	3.00	3.00	3.00
20	3.00	3.00	3.00	3.00	3.00	3.00	3.00
21	3.00	3.00	3.00	3.00	3.00	3.00	3.00
22	3.00	3.00	3.00	3.00	3.00	3.00	3.00
23	3.00	3.00	3.00	3.00	3.00	3.00	3.00

The program performs two data checks: one, to see if the collector data is reasonable, two, to see if the systems data is reasonable. If either check fails, the program prints a warning and returns the user to the input section. The three warnings are:

1 * **THE MAXIMUM FLOW RATE TO COLLECTOR AREA IS 0.001 M3/(M2*S)**

* THE MINIMUM ALLOWABLE VALUE IS 0.002 :
THE COLLECTOR AREA IS TOO SMALL OR THE MAXIMUM FLOW RATE TOO LARGE

2 * **THE MAXIMUM FLOW RATE TO COLLECTOR AREA IS 0.100 M3/(M2*S)**

* **THE MAXIMUM ALLOWABLE VALUE IS 0.05 :**
THE COLLECTOR AREA IS TOO LARGE OR THE MAXIMUM FLOW RATE TOO SMALL

3 * **THE MAXIMUM FLOW RATE TO COLLECTOR AREA IS 0.010 M3/(M2*S)**

* WITH THE GIVEN TEST CONDITIONS THE COLLECTOR HAD AN FR OF 0.77
UNDER THE SAME CONDITIONS THE PROGRAM CALCULATES AN FR OF 0.53

Then the program will print:

* **PROGRAM CANNOT ACCURATELY SIMULATE SYSTEM WITH THE PARAMETERS CHOSEN**

* **PLEASE RE-CHECK INPUT DATA**

If the data checks are successful the system is simulated and the results are printed on a monthly basis with a yearly summary at the end.

WHEN TESTED THE COLLECTOR HAD AN FR OF 0.77
UNDER THE SAME CONDITIONS THE PROGRAM CALCULATES AN FR OF 0.77

****

PERFORMANCE PREDICTION

****

MONTH	FRACTION SOLAR	SOLAR CONTRIB (GJ)	TOTAL LOAD (GJ)	SOLAR RAD. (GJ)	DEGREE DAYS C-DAY	AMBIENT TEMP. DEG C
1	0.07	22.7	322.4	37.0	960.	-13.0
2	0.08	19.7	246.0	32.3	724.	-7.9
3	0.16	38.0	234.5	61.9	682.	-4.0
4	0.20	32.5	161.5	55.6	452.	2.9
5	0.21	16.1	76.1	57.2	189.	12.6
6	0.21	6.6	31.1	62.0	63.	18.0
7	0.22	4.7	21.7	56.9	37.	19.0
8	0.23	8.1	34.7	56.0	72.	17.6
9	0.21	9.2	44.3	42.1	96.	15.9
10	0.14	13.3	98.5	31.0	252.	10.0
11	0.07	14.3	194.5	23.6	557.	-0.6
12	0.06	15.5	262.4	25.4	770.	-6.8
YEAR	0.12	200.7	1727.7	541.0	4853.	

THE AVERAGE COLLECTION EFFICIENCY OVER THE YEAR IS 0.37

THE YEARLY SOLAR CONTRIBUTION PER SQUARE METRE IS 2.01 GJ/M2/YR

THE MAX. VALUE OF FR IS 0.825 OCCURING WHEN
SOLAR RAD. IS 863.4 W/M2 AND AMB TEMP IS 30.0 C

The program then asks the user if another run is to be made.

```
DO YOU WISH TO CONTINUE ? (Y/N)
y
ARE ALL THE VALUES CORRECT ? (Y/N)
n
DO YOU WISH TO CHANGE SOLAR RADIATION SECTION ? (Y/N)
n
DO YOU WISH TO CHANGE COLLECTOR SECTION ? (Y/N)
y
```

To simulate the performance of the system in a different city, the user must answer N and restart with the VENTAIR command and the name of the new city.

The previous example was for one of the PUSH approved collectors. If another collector is to be used, the program will prompt for the collector characteristics.

```
*** COLLECTOR SECTION ***
 THE PROGRAM HAS DATA FOR 4 SOLAR COLLECTORS :
      1 - AMHERST 200
      2 - SOLARTECH SOLAIR
      3 - WATERSHED A100 (NARROW CHANNEL)
      4 - WATERSHED A100 (WIDE CHANNEL)

  SELECT THE COLLECTOR TO BE SIMULATED
  (USE ZERO FOR A COLLECTOR NOT LISTED ABOVE, HOWEVER IT MUST BE
     A PARALLEL PLATE COLLECTOR, NOT A FIBRE MATRIX COLLECTOR)
0
ENTER COLLECTOR FRTA
0.60
ENTER COLLECTOR FRUL  (W/M**2/C)
4.0
ENTER TRANSMISSION-ABSORPTION PRODUCT
0.9
ENTER RATIO OF COLLECTOR APERATURE TO GROSS AREA
0.9
ENTER COLLECTOR TEST FLOW RATE  (M**3/M**2/S)
0.01
ENTER COLLECTOR FLOW CHANNEL HEIGHT  (M)
0.05
ENTER COLLECTOR FLOW CHANNEL LENGTH  (M)
2.
```

In addition to selecting a constant ventilation rate, the user can have two ventilation rates per day, or a different ventilation rate for each hour of the week.

```
*** VENTILATION RATE SCHEDULE SECTION ***

ENTER LOAD SCHEDULE TYPE....
1 - CONSTANT VENTILATION RATE
2 - TWO VENTILATION RATES PER DAY
3 - VENTILATION RATE DIFFERENT FOR EACH HOUR
2
ENTER DAY VENTILATION RATE  (M**3/S)
3.
ENTER NIGHT VENTILATION RATE  (M**3/S)
0.
ENTER HOUR (0 - 23) THAT DAY RATE STARTS FOR DAY 1
9
ENTER HOUR (0 - 23) THAT DAY RATE STOPS FOR DAY 1
17
ENTER HOUR (0 - 23) THAT DAY RATE STARTS FOR DAY 2
9
ENTER HOUR (0 - 23) THAT DAY RATE STOPS FOR DAY 2
17
ENTER HOUR (0 - 23) THAT DAY RATE STARTS FOR DAY 3
9
ENTER HOUR (0 - 23) THAT DAY RATE STOPS FOR DAY 3
17
ENTER HOUR (0 - 23) THAT DAY RATE STARTS FOR DAY 4
9
ENTER HOUR (0 - 23) THAT DAY RATE STOPS FOR DAY 4
17
ENTER HOUR (0 - 23) THAT DAY RATE STARTS FOR DAY 5
9
ENTER HOUR (0 - 23) THAT DAY RATE STOPS FOR DAY 5
17
ENTER HOUR (0 - 23) THAT DAY RATE STARTS FOR DAY 6
0
ENTER HOUR (0 - 23) THAT DAY RATE STOPS FOR DAY 6
0
ENTER HOUR (0 - 23) THAT DAY RATE STARTS FOR DAY 7
0
ENTER HOUR (0 - 23) THAT DAY RATE STOPS FOR DAY 7
0
```

```
*** VENTILATION RATE SCHEDULE SECTION ***

ENTER LOAD SCHEDULE TYPE....
1 - CONSTANT VENTILATION RATE
2 - TWO VENTILATION RATES PER DAY
3 - VENTILATION RATE DIFFERENT FOR EACH HOUR
3
ENTER THE 24 VALUES FOR VENTILATION RATE (M3/S) FOR DAY 1
0.,0.,0.,0.,0.,0.,0.,3.,3.,3.,3.,3.,3.,3.,3.,5.,5.,5.,0.,0.,0.,0.,0.
ENTER THE 24 VALUES FOR VENTILATION RATE (M3/S) FOR DAY 2
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,6.,6.,6.,6.,6.,0.,0.,0.,0.,0.,0.
ENTER THE 24 VALUES FOR VENTILATION RATE (M3/S) FOR DAY 3
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,1.,1.,1.
0.,0.,0.,0.,0.,0.,0.,0.,0.
ENTER THE 24 VALUES FOR VENTILATION RATE (M3/S) FOR DAY 4
0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.
ENTER THE 24 VALUES FOR VENTILATION RATE (M3/S) FOR DAY 5
1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1.
ENTER THE 24 VALUES FOR VENTILATION RATE (M3/S) FOR DAY 6
0.,0.,0.,0.,0.,4.,4.,4.,4.,4.,6.,6.,6.,6.,6.,6.,6.,6.,6.,6.,0.,0.,0.,0.
ENTER THE 24 VALUES FOR VENTILATION RATE (M3/S) FOR DAY 7
0.,0.,0.,0.,0.,0.,9.,9.,9.,9.,9.,9.,9.,9.,99.,9.,9.,9.,9.,9.,9.,0.,0.
```

Note that the hourly values can be separated by a blank or a comma and need not be all on one line.

3. SYSTEM INPUT PARAMETERS

The following sections describe the parameters used in the VENTAIR-2 computer program. The user must ensure that the parameters are in the appropriate units.

3.1 Definition of Input Parameters

SOLAR RADIATION SECTION

COLLECTOR SLOPE (DEG.)

The angle that the collector is tilted from the horizontal in degrees. (Range 0. to 90.)

COLLECTOR AZIMUTH ANGLE - SOUTH = 0 (DEG.)

The number of degrees that the collector is oriented off due south (east is positive, west is negative). (Range -90. to 90.)

LOCATION LATITUDE (DEG.)

The latitude of the location that is being simulated in degrees. See Section 3.2 for values.

COLLECTOR SECTION

The program has default values for four solar collectors. The user must specify a number between one and four to select the appropriate collector. If the number 0 (not the letter O) is selected, the user may input collector parameters of other collectors. The program checks these parameters to ensure consistency. The program will not run if the input parameters are not realistic. The input parameters required if the number 0 is selected are described below. These parameters apply only to a parallel plate solar collector and not a fibre matrix collector.

COLLECTOR FRTA

The $F_R\tau\alpha$ of the collector as determined from certified performance testing (based on gross collector area). Available from collector data sheets.

COLLECTOR FRUL (W/M**2/C)

The F_RU_L of the collector as determined from certified performance testing in $W/m^2/°C$ (based on gross collector area). Available from collector data sheets.

TRANSMISSION-ABSORPTION PRODUCT

The $(\tau\alpha)$ effective of the collector. This can be estimated as 1.01 times $\tau\alpha$ for a single glazed collector where τ is the glazing solar transmission and α is absorber solar absorptivity.

RATIO OF COLLECTOR APERTURE TO GROSS AREA

The ratio of the collector aperture area (i.e. window area) to the gross area. Typically this value is usually close to 0.9, actual values can be obtained from collector data sheets.

COLLECTOR TEST FLOW RATE (M**3/(M**2·S))

The flow rate per unit area used when the collector parameters $F_R\tau\alpha$ and F_RU_L were determined. It is important to note that the units are M^3/s per square metre of gross collector area. This parameter is ususally close to 0.01 $m^3/(m^2 \cdot s)$.

COLLECTOR FLOW CHANNEL HEIGHT (M)

The spacing between the upper and lower absorber plates in metres. For a curved upper absorber use the average spacing. (Range 0.01 to 0.1) In general decreasing the flow channel height increases the collector F_R although this will result in a higher collector pressure drop.

COLLECTOR FLOW CHANNEL LENGTH TEST CONDITIONS (M)

The distance or length that the air stream is in contact with the absorber plate. In most collectors this will be the length of collector in the flow direction times the number of collectors in series when tested. In some cases collectors are designed so that the contact length is much shorter than the collector such as the overlapped glass plate. Increasing the flow channel length increases the flow rate through each collector. This results in an improved F_R but at increased collector pressure drop.

SYSTEMS SECTION

REQUIRED BUILDING OR PROCESS TEMPERATURE (C)

The desired temperature of air entering the building or process in Celsius. For ventialtion air, this value would be the thermostat set point. For process air, this value would be the process air temperature. There is no upper limit on the process temperature although a high process temperature will result in a low fraction solar.

GROSS COLLECTOR AREA (M**2)

The gross collector area in square metres.

MAXIMUM ALLOWABLE SOLAR SYSTEM FLOW RATE (M**3/S)①

The maximum flow rate that can be drawn by the solar collectors in m^3/s. This value would normally be equal to the maximum ventilation rate, however in cases of high ventilation rate where a small collector area is used the maximum collector flow rate would be less than the ventilation rate. A reduced value is used because at high flow rates the incremental fan power consumption exceeds the incremental solar contribution. The user should check with the collector manufacturer for the maximum allowable collector flow rate. Typically the maximum collector flow rate should result in a static pressure loss of less than 250 Pa.

① $1 m^3/s$ = 2119 cfm

Note that this parameter is a total system flow and not a per unit collector area flow.

ARRAY FLOW PATH LENGTH (M)

This is the total distance or length that the air stream is in contact with the absorber. In most cases this value would be the length of the collector in the flow direction times the number of collectors in series. For short path collectors see the note under COLLECTOR FLOW CHANNEL LENGTH in Section 3.1.

PROCESS OR VENTILATION RATE SCHEDULE SECTION

The air flow rate can be varied for every hour of a 7 day cycle. The user can input the air flow rate in one of three ways:

1. constant air flow rate all week
2. two air flow rates per day
3. a different air flow rate for each hour

Process or ventilation rates selected should be the total air flow rate into the building even if this flow rate does not all go through the collectors.

3.2 Weather Data

At present there is weather data for 46 cities that can be used by the program. These cities are tabulated below. The solar radiation data as supplied by Atmospheric Environment Service is of two types: derived or measured. Measured data is as recorded by their monitoring equipment (with missing data estimated from the previous day's values). Derived data is predicted by using other meteorological data such as rainfall, cloud cover etc.

City	Province	Latitude (Deg.)	Year	Solar Rad. Derived/Measured
Victoria	B.C.	48.7	1971	D
Prince George	B.C.	53.9	1974	M
Vancouver	B.C.	49.2	1971	M
Summerland	B.C.	49.6	1971	D
Frobisher Bay	N.W.T.	63.8	1975	D
Resolute	N.W.T.	74.7	1971	M
Edmonton	Alta.	53.6	1971	M
Medicine Hat	Alta.	50.0	1971	D
Uranium City	Sask.	59.6	1971	D
Swift Current	Sask.	50.3	1971	D
Saskatoon	Sask.	52.2	1971	D
Churchill	Man.	58.8	1975	D
Brandon	Man.	49.9	1971	D
Winnipeg	Man.	49.9	1971	M
The Pas	Man.	53.8	1971	M
Thunder Bay	Ont.	48.4	1971	D
Sault Ste. Marie	Ont.	46.5	1971	D
Sudbury	Ont.	46.5	1971	D
Kapuskasing	Ont.	49.4	1966	M
Kingston	Ont.	44.2	1971	D
Muskoka	Ont.	45.0	1971	D
Windsor	Ont.	42.3	1971	D
London	Ont.	43.0	1971	D
Toronto	Ont.	43.7	1971	M
Ottawa	Ont.	45.4	1971	M

Montreal	Que.	45.5	1971	M
Sept. Iles	Que.	50.2	1974	M
Quebec	Que.	46.8	1971	D
Sherbrooke	Que.	45.4	1971	D
Riviere du Loop	Que.	47.8	1971	D
Bagotville	Que.	48.3	1971	D
Val D'Or	Que.	48.0	1971	D
Fredericton	N.B.	45.9	1971	M
Charlo	N.B.	48.0	1971	D
Chatham	N.B.	47.0	1971	D
Moncton	N.B.	46.1	1971	D
St. John	N.B.	45.3	1971	D
Charlottetown	P.E.I.	46.3	1971	D
Truro	N.S.	45.4	1971	D
Halifax	N.S.	44.7	1971	M
Sydney	N.S.	46.2	1971	D
Yarmouth	N.S.	43.8	1971	D
St. John's	Nfld.	47.6	1971	M
Gander	Nfld.	49.0	1971	D
Stephenville	Nfld.	48.5	1971	D
Goose	Nfld.	53.3	1971	M

4. DESCRIPTION OF PROGRAM OUTPUT

At the conclusion of each simulated month, results are printed. The results are an estimate of the performance of a properly designed and installed system. Because the system has no thermal storage, it is possible to adjust the system performance according to the number of days of operation. For example the solar contribution of a 5 day on - 2 day off ventilation schedule would be 5/7 of a 7 day on schedule.

The output values are:

MONTH

The month of the simulation, January is 1, December is 12.

FRACTION SOLAR

The fraction of the total heating load that is met by the solar heating system. This value can be misleading if it is not taken in context with the ventilation or process air rate schedule. Because there is no thermal storage, the solar heating system cannot meet any of the night time heating demand. Thus, a building that ventilates evenly 24 hours a day could never have a fraction solar over 0.4. Whereas a building that ventilates for only one hour per day at noon could have a fraction solar of over 0.70. The first system, however, is probably the more cost effective.

SOLAR CONTRIB (GJ)

The amount of solar energy that is used to heat the process or ventilation air. Alternatively this value can be thought of as the reduction in auxiliary energy to heat the air.

TOTAL LOAD (GJ)

The energy required to heat the process or ventilation air if there were no solar heating system.

SOLAR RAD. (GJ)

The total solar radiation incident on the gross collector area, regardless of whether the system is operating.

DEGREE - DAYS (C-DAY)

The number of degree-days based on 18°C. This is a measure of how cold the location is.

AMBIENT TEMP. (DEG. C)

The average ambient or outdoor temperature for the time period.

AVERAGE COLLECTION EFFICIENCY OVER THE YEAR

The yearly solar contribution divided by the solar radiation. It is important to note that if the daily air flow schedule is very short this value will be low regardless of the collector performance curve.

YEARLY SOLAR CONTRIBUTION PER SQUARE METRE

The yearly solar contribution divided by the collector area. A good application of a solar preheated ventilation air system would have a value of over 1.0 $GJ/m^2/yr$.

MAX. VALUE OF FR

The maximum value of the collector heat removal factor (F_R) for any hour during the simulation. If this value is below the test value of F_R, the system may not be well designed, i.e. collector flow rate too low or collector area too large.

5. PROGRAM ALGORITHM

5.1 Overview of Program Operation

The VENTAIR-2 computer program calculates the performance of solar preheated process or ventilation air systems on an hour-by-hour basis. The basic assumption of the program is that for the purpose of calculating performance all variables, including solar radiation, ambient temperature and building ventilation rate can be considered constant for each hour. Thus, if the building ventilation rate varies widely within a given hour, the VENTAIR-2 program is not applicable. An example of a system where VENTAIR-2 is not applicable is a bathroom ventilation system operated by a light switch or short duration timer.

The program calculation flow chart is shown in Figure 2. The first step in the program is the input of the input parameters in an interactive manner. Section 3. gives a full description of the input parameters. After all the parameters have been entered,the program calculates the collector heat removal factor for the test values of flow rate and flow path length using the method given in Section 5.2. This value is compared to the value of F_R found from the collector $F_R\tau\alpha$ term.

The two values are printed at the terminal. At the test condition, the calculated value of F_R will be either higher or lower than the test value. If the difference between the values if greater than 15% the program prints a warning and returns to the input mode. A check is also made on the collector flow rate. If the collector flow rate per unit area is not reasonable (minimum value 0.002 $m^3/(m^2.s)$,maximum value 0.05 $m^3/(m^2.s)$) the program prints a warning and returns to the input mode.

Each time new values are given to the variables in the solar radiation section the solar radiation on a tilted surface is recalculated. The algorithm

for performing this calculation is given in Section 5.3.

When the solar radiation and the input parameters are correct, the program begins the simulation at January 1st. A new value of solar radiation and ambient temperature is read for each simulated hour and the process or ventilation air heating load is calculated (Q_L). If the load is zero the program goes to the next hour. If the solar radiation is zero the load is added to the previous load values and the program moves to the next hour.

If the solar radiation and heating load are greater than zero, F_R is calculated for that hour's flow rate and meteorological conditions. The equations for F_R are given in Section 5.2. The maximum solar contribution is calculated with the equation:

$$Q_S = F_R \cdot (\tau\alpha)_e \cdot I \cdot A$$

The inlet temperature to the building (T_{in}) is calculated based on Q_S.

$$T_{in} = T_a + Q_S/(\dot{m}\, C_p)$$

If this temperature is greater than the desired temperature T_{bg}, then Q_S is made equal to Q_L. The values of Q_S and Q_L are added to the previous values and the program moves to the next hour.

At the end of each simulated month, the monthly totals of solar contribution and heating load are printed. A full description of the output is given in Section 4.

5.2 Algorithm for the Calculation of F_R

Two separate algorithms are used for the calculation of F_R, one for parallel plate solar collectors and one for fibre matrix solar collectors. It is important to note that a correction on F_R for the number of collectors in series is not necessary provided that the mass flow per unit area is kept constant.

Figure 2: VENTAIR-2 Program Flow Chart

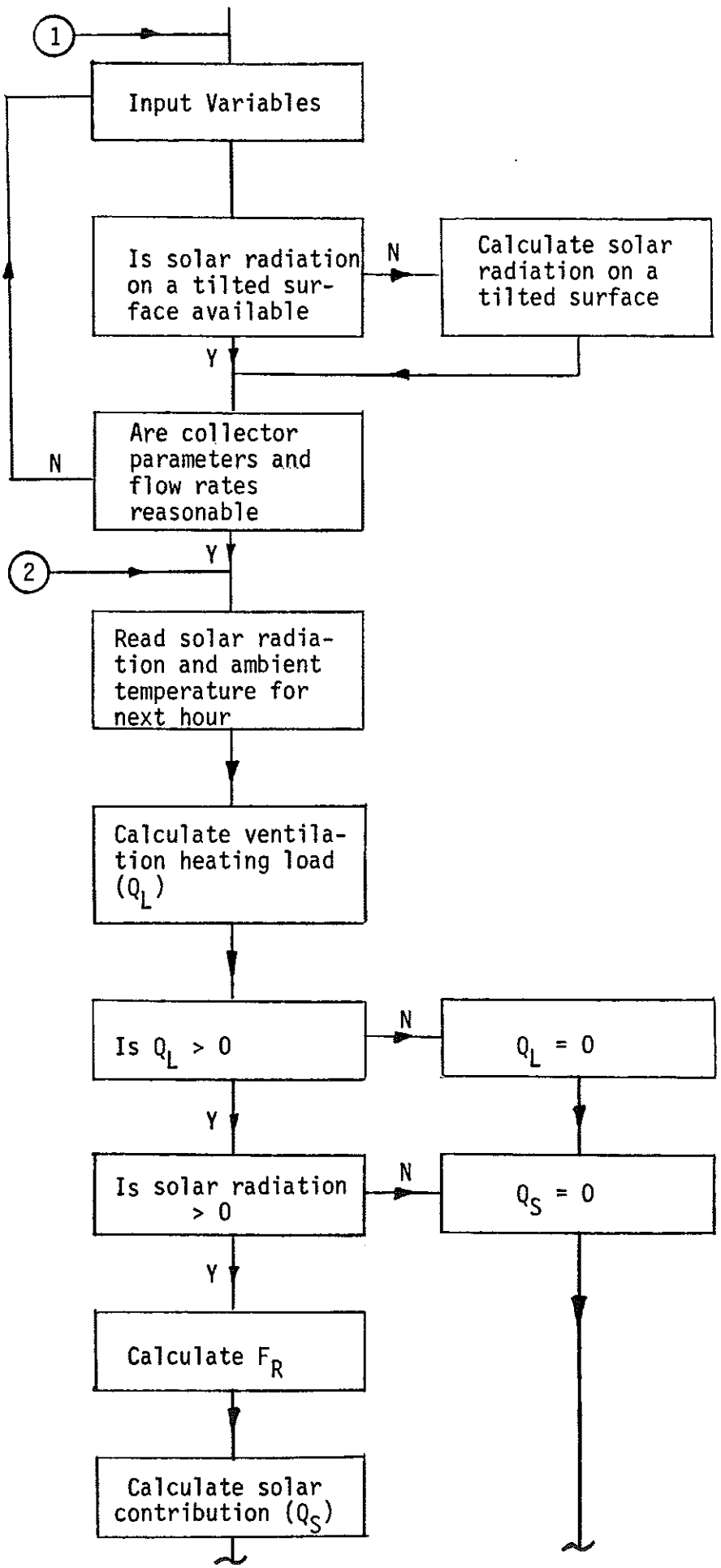
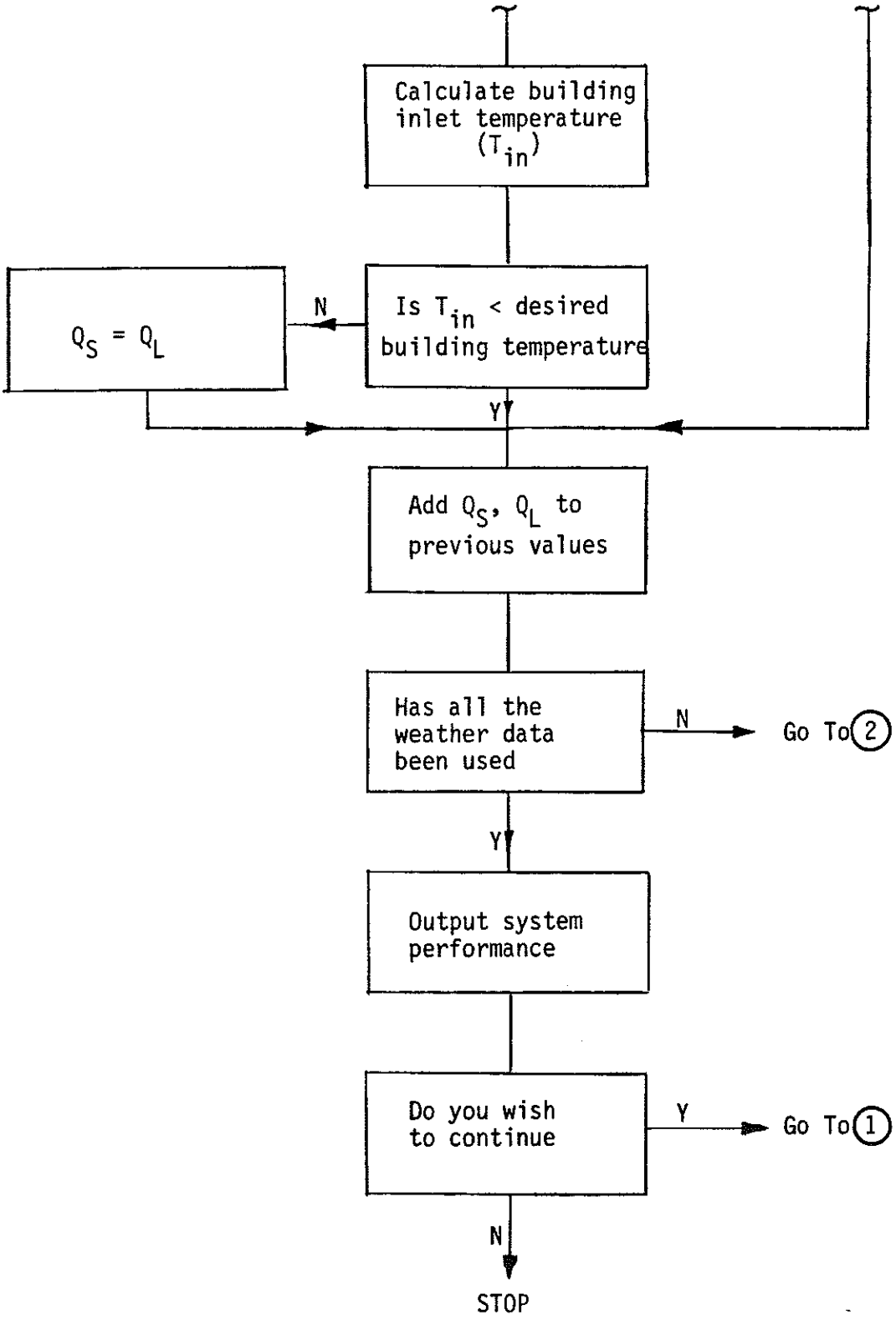


Figure 2: VENTAIR-2 Program Flow Chart (cont'd)



i) F_R for Parllel Plate Solar Collectors

F_R is given by:

$$F_R = \frac{\dot{m}\ Cp}{U_L} \cdot (1 - \exp(-F'U_L/(\dot{m}\ Cp)$$

where $F' = U_o/(U_o + U_L)$

All of the variables are constant except for $\dot{m}$ (mass flow rate per unit area) and U_o (the total plate to fluid heat transfer coefficient). $\dot{m}$ is given each hour by the air flow rate schedule, thus, a new value of U_o must be calculated for each hour. U_o depends on the collector design.

The equations for U_o given below were taken from:

Hollands, K.G.T. and Shewen, E.C., Journal of Solar Energy Engineering, Vol. 103, No. 4, November, 1981. "Optimization of Flow Passage Geometry for Air-Heating, Plate-Type Solar Collectors".

$$U_o = h_{pf} + h_{pf} \cdot h_r/(h_r + h_{pf})$$

where h_r is the radiative heat transfer coefficient between the upper and lower absorber plates

if we assume that the inside of the air channel is painted black:

$$h_r = \sigma(T_1^2 + T_2^2)\ (T_1 + T_2)/(1.222)$$

where T_1 and T_2 are the temperatures of the upper and lower absorber plates

h_{pf} is the convective heat transfer coefficient between the plate and the air stream

$$h_{pf} = Nu \cdot k/(2.b)$$

where k is the conductivity of air

b is the spacing between the upper and lower absorber plates

Nu is the Nusselt number.

for Re < 2000 (Reynolds number)

$$Nu = 5.385 + 0.148 \cdot Re \cdot b \cdot n/L$$

n is the number of air flow passage channels (typically equal to 1)

L is the collector flow path length

for 2000 < Re < 10000

$$Nu = 0.00044 \cdot Re^{1.2} + 9.37 \cdot Re^{0.471} \cdot b \cdot n/L$$

for 10000 < Re ≤ 100000

$$Nu = 0.03 \cdot Re^{0.74} + 0.788 \cdot Re^{0.74} \cdot b \cdot n/L$$

where $Re = \frac{2 \dot{m} L}{\mu}$

if Re is greater than 100000 the program sets Re equal to 100000.

ii) F_R for Fibre Matrix Collectors (see Figure 3)

The estimation of F_R for fibre matrix collectors requires a different formulation for F_R. F_R can be thought of as the ratio of the actual useful energy to the useful energy if the absorber plate were at the fluid inlet temperature (T_{fi}). For a ventilation collector F_R is:

$$F_R = \frac{\tau\alpha.I - U_L(T_{ave} - T_{fi})}{\tau\alpha.I - U_L(T_{fi} - T_{fi})} = 1 - \frac{U_L(T_{ave} - T_{fi})}{\tau\alpha.I}$$

where T_{ave} is the average temperature that the collector loses heat at. This temperature is normally the average plate temperature, however, a fibre matrix collector has inlet air blowing across the lower glazing thus loses heat from a lower temperature. For a fibre matrix collector T_{ave} is:

$$T_{ave} = (h_r T_{plate} + h_{pf} T_{fi})/(h_r + h_{pf})$$

where h_{pf} is the convective heat transfer coefficient between the lower glazing and the air stream

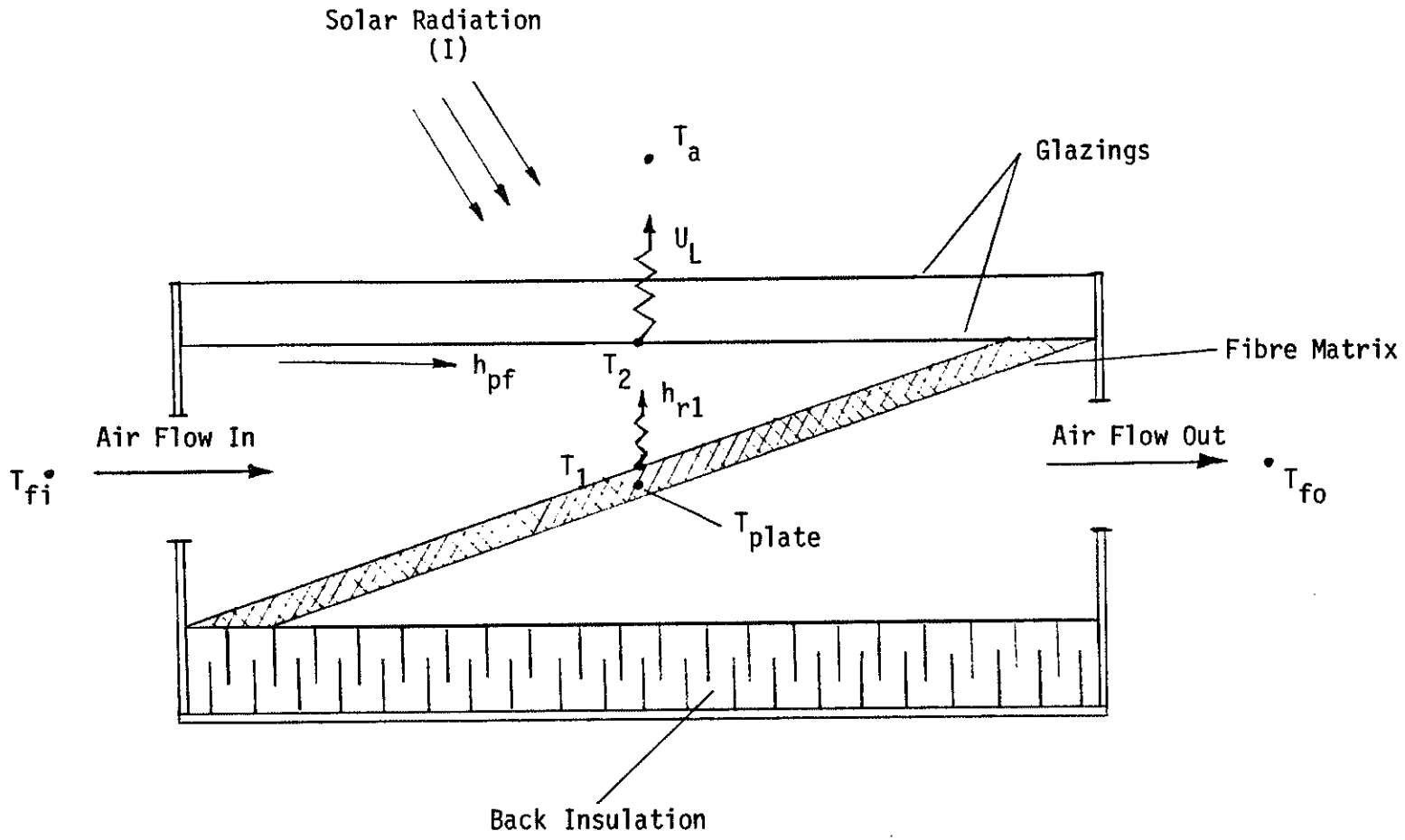


Figure 3: Schematic of Fibre Matrix Solar Collector

h_r is the radiative heat transfer coefficient between the fibre matrix and the lower glazing. Because of the nature of the fibre matrix, h_r is a weighted average of the value of h_r for each layer of fibres with the top layer having a weighting of 1 and the bottom layer having a weighting of 0. By integrating the values for h_r over the depth of the matrix, h_r can be approximated by:

$$hr = h_{r1}/3 + h_{r2}/6$$

where $h_{r1} = \sigma (T_1^2 + T_2^2) (T_1 + T_2)/1.222$

$$h_{r2} = \sigma (T_{fo}^2 + T_2^2) (T_{fo} + T_2)/1.222$$

T_1 is the temperature of the top of the fibre matrix

T_2 is the temperature of the lower glazing

The average fibre matrix plate temperature can be calculated by:

$$T_{plate} = T_{fm} + Qu/U_o$$

where U_o is the fibre matrix to air heat transfer coefficient.

T_{fm} is the average fluid temperature

Estimating U_o for fibre matrix collectors is much more difficult than for parallel plate collectors. The reference used for these equations is:

Kays, W. and London, A.L., Compact Heat Exchangers Second Edition, McGraw-Hill, New York, 1964, pg. 129.

For fibre matrices Kays and London give equations of the form:

$$U_o = x \left(\frac{A_{fm}}{A_c}\right) \cdot \dot{m} \cdot Cp / (Re^y \cdot Pr^{2/3})$$

where Pr is the Prandtl number

where x and y are constants dependent on the type and shape of the matrix.

For a similar type of fibre matrix Kays and London give:

$x = 1.3$ $\quad$ $y = 0.45$

By knowing the average fibre matrix diameter and the fibre matrix mass, the ratio of heat transfer to collector area can be calculated. For the Amherst collector

$$\frac{A_{fm}}{A_c} \cong 80.$$

5.3 Algorithm to Process Weather Data

Most Canadian weather stations measure only total solar radiation on a horizontal surface. Most solar collectors, however, are tilted toward the sun to increase the incident solar radiation. The program determines hourly values of total solar radiation (beam, diffuse and reflected) on a tilted surface and stores the values in a scratch file. The algorithm for converting horizontal solar radiation to tilted solar radiation is similar to the method used in "Solar Engineering of Thermal Processes"by Duffie and Beckman (2).

In order to estimate the solar radiation on a tilted surface it is necessary to split the total measured horizontal solar radiation into its two components: beam and diffuse. It is possible to estimate the amount of diffuse solar radiation from the ratio of the measured solar radiation to the extraterrestrial solar radiation. If this ratio is low then the solar radiation must be mostly diffuse; if this ratio is high the solar radiation must be mostly beam.

When the beam and diffuse solar radiation components are known, standard geometric relations can be used to estimate the solar radiation components on a tilted surface. When estimating solar radiation on a tilted surface a third component is introduced: reflected radiation. Reflected radiation can be estimated from the beam radiation and the ground albedo or reflectivity.

The program equations and execution procedure are given below.

At the start of each day the solar constant and the earth's solar declination are calculated. The solar constant is given by:

$$S_C = 4871.0\ (1. + 0.33 \cos\ (2\pi N / 365) \qquad \text{in KJ/(hr*m}^2\text{)}$$

where N is the day number (Jan 1 is 1).

The earth's declination is given by:

$$\delta = \frac{23.45 * 2\pi}{360} * \sin\ \left(\frac{2\pi\ (284 + N)}{360 * 365}\right) \qquad \text{(in radians)}$$

These values are assumed constant for each day. All other calculations are made on an hourly basis.

The first step is to read the measured weather values from the data file. For each hour the weather data file contains six values in the following order.

1) month number (1-12)
2) day number (1-31)
3) hour number (1-24)
4) ground reflectivity
5) solar radiation on a horizontal surface (in Watts/m^2)
6) ambient temperature (in °C)

The extraterrestrial solar radiation on a horizontal surface is calculated by:

$$H_{ex} = S_C \cdot \cos\ (\theta_z)$$

where $\cos\ (\theta_z)$ is cosine of the zenith angle (angle between the beam and the vertical)

$$\cos\ (\theta_z) = \cos\ (\phi) \cos\ (\delta)\ \cos w + \sin\phi\ \sin\delta$$

ϕ is the latitude of the location

w is the hour angle.

The diffuse solar radiation (H_d) can be estimated using a correlation by Orgill and Hollands (3).

$$H_d = 0.1769\ H \qquad \text{if } 0.75 < K_T$$

$$H_d = (1.55699 - 1.84013 \cdot K_T) \cdot H \qquad \text{if } 0.35 \leq K_T \leq 0.75$$

$$H_d = (1. - 0.248857 \cdot K_T) \cdot H \qquad \text{if } 0.0 \leq K_T \leq 0.35$$

where H is the measured hourly solar radiation

K_T is the ratio of measured solar radiation to the extraterrestrial solar radiation
$= H / H_{ex}$

The beam radiation (H_b) is simply the total measured solar radiation minus the diffuse radiation.

$$H_b = H - H_d$$

The next step is to calculate the ratio of beam radiation on the tilted surface to that on the horizontal surface (R_b).

$$R_b = \cos(\theta_T) / \cos(\theta_z)$$

where $\cos(\theta_T)$ is the cosine of the angle of incidence of beam radiation, between the beam and the normal to the surface.

$$\cos(\theta_T) = \sin(\delta)\sin(\phi)\cos(s) - \cos(\delta)\cos(\phi)\cos(s)\cos(w) + \cos(\delta)\sin(\phi)\sin(s)\cos(\gamma)\cos(w)\cos(\delta)\sin(s)\sin(\gamma)\sin(w)$$

γ is the azimuth angle measured from south (east is positive, west is negative)

Thus, the beam solar radiation on the tilted surface is

$$H_{bT} = R_b\ H_b$$

The diffuse solar radiation component on the tilted surface is estimated using the radiation view factor from the collector to the sky with correction factors for non-uniform distribution of diffuse radiation.

The correction factors for anisotropic diffuse radiation are taken from Temps and Coulson (4) and Klucher (5). The resulting equation is:

$$H_{dT} = \left(\frac{1 + \cos(s)}{2}\right) (1 + F \sin^3(s/2)) (1 + F \cos^2(\theta_T) \cdot \sin^3(\theta_z)) H_d$$

where $F = 1 - (H_d/H)^2$

The reflected solar radiation on the tilted surface (H_r) is

$$H_r = \left(\frac{1 - \cos(s)}{2}\right) \rho H$$

where ρ is the ground reflectivity

The total solar radiation on the tilted surface (H_T) is the sum of the beam diffuse and reflected solar radiation components.

Hourly values of total solar radiation on a tilted surface, ambient temperature, day number and hour number are written to the scratch file. When all the data has been processed and written to the scratch file, the file is rewound to be ready for the system simulation.

6. PROGRAM STRUCTURE

The program structure is described in this section. Only those individuals interested in modifying the program need read this section.

The program flow chart is shown in Figure 4. The program consists of a mainline and four subroutines:

1) MAINLINE - main program for file unit number allocation and calling of subroutines

ii) INPUT - interactive subroutine for user input of data and printing of input data

iii) WEATH - subroutine for converting measured horizontal solar radiation to the tilted surface

iv) VENT - subroutine to calculate system performance on an hourly basis

v) FRCALC - subroutine to calculate the collector heat removal factor F_R for a given set of meteorological conditions and flow rate

Four file definitions must be made before the program can be run:

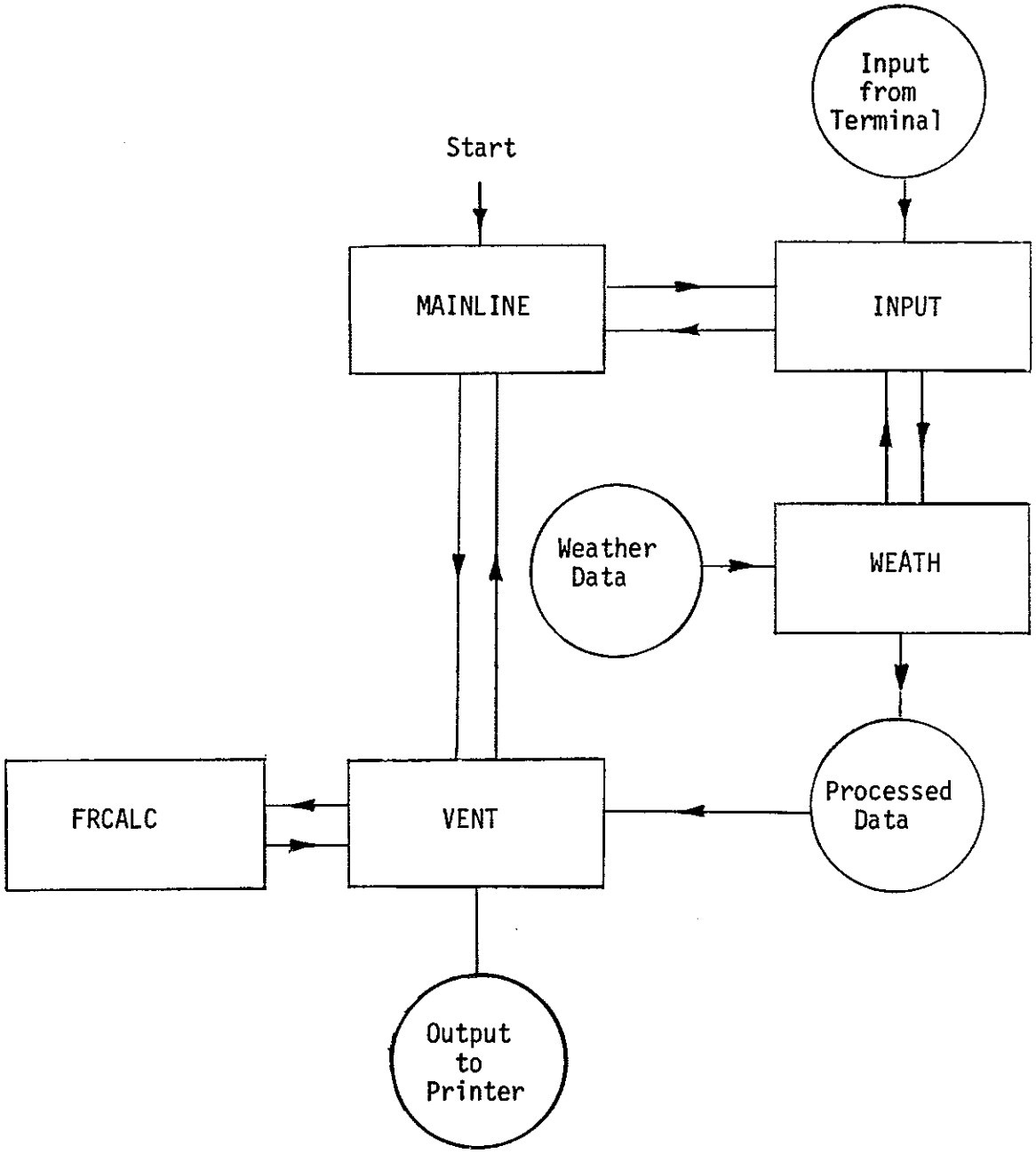
Terminal - (Unit 8) is the device used for data input. The program will send all questions and prompts to this device.

Printer - (Unit 6) is the device that receives the output (i.e. a printer). If a send and receive printer is being used unit 6 and 8 will be the same device.

Weather Data - (Unit 9) is the file containing the TRNSYS compatible weather data. The data must be written in the format (2X, I2, 2X, I2, 2X, I2, F3.1, I3, F6.1) and contain month number, day number, hour number, ground reflectivity, ambient temperature (°C), and solar radiation on a horizontal surface (W/m^2).

Processed Data - (Unit 10) is the file that is created by the program containing the solar radiation on the tilted surface and ambient temperature.

Figure 4: VENTAIR-2 Program Structure



7. REFERENCES

1) Morton, B. and Carpenter, S., Use of Air-based Solar Collectors to Preheat Ventilation Air, 1981 Solar Energy Society of Canada Inc. Conference, Montreal, 1981.

2) Duffie and Beckman, Solar Engineering of Thermal Processes, John Wiley and Sons, New York, 1980.

3) Orgill, J.F. and Hollands, K.G.T., Solar Energy, Vol. 19, No. 2, "Correlation Equation for Hourly Diffuse Radiation on a Horizontal Surface".

4) Temps, R.C. and Coulson, K.L., Solar Energy, Vol. 19, No. 2, "Solar Radiation Incident upon Slopes of Different Orientation".

5) Klucher, T.M., Solar Energy, Vol. 23, No. 2, "Evaluation of Models to Predict Insulation on Tilted Surfaces".

8. INPUT DATA WORK SHEET

VENTAIR-2 Input Data

Solar Radiation Data

Collector Slope (degrees) _____

Collector Azimuth (degrees) _____

Location Latitude (degrees) _____

Collector Test Data

Select from 1 to 4 for default collector parameters.

or if zero is selected enter...

$F_R\tau\alpha$ _____

F_RU_L ($W/m^2/°C$) _____

Transmission-Absorption Product ($\tau\alpha$) _____

Aperture to Gross Area Ratio _____

Collector Test Flow Rate ($m^3/(s-m^2)$) _____

Channel Height b (m) _____

Flow Length (Test Conditions) _____

Systems Data

Collector Area (m^2) _____

Maximum Solar System Flow Rate (m^3/s) _____

Building or Process Temperature (C) _____

Array Flow Length _____

Process or Ventilation Rate Schedule

1 - Constant Air Flow Rate all week

2 - Two Air Flow Rates per day

3 - Air Flow Rate different for each hour (168 values)

9. NOMENCLATURE

A	total collector area (m^2)
A_c	area of one collector (m^2)
A_{fm}	surface area of fibre matrix (m^2)
b	collector channel height (m)
C_p	specific heat (KJ/(kg·°C)
F'	$U_o/(U_o + U_L)$
F_R	collector heat removal factor
$F_R\tau\alpha$	collector transmission-absorption coefficient
F_RU_L	collector heat loss coefficient (W/(m^2·°C)
H	measured hourly solar radiation (KJ/(hr·m^2)
H_b	beam hourly solar radiation (KJ/(hr·m^2)
H_{bT}	beam hourly solar radiation on a tilted surface (KJ/(hr·m^2)
H_d	diffuse hourly solar radiation (KJ/(hr·m^2)
H_{dT}	diffuse hourly solar radiation on a tilted surface (KJ/(hr·m^2)
H_{ex}	extraterrestrial hourly solar radiation (KJ/(hr·m^2)
hpf	plate to fluid convective heat transfer coefficient
hr	radiative heat transfer coefficient
H_r	reflected hourly solar radiation (KJ/(hr·m^2)
I	total incident solar radiation (KJ/(hr·m^2)
K_T	clearness index
L	length of collector in flow direction (m)
$\dot{m}$	mass flow rate (kg/hr)
n	number of air flow passage channels
N	day number of the year
Nu	Nusselt Number

QL	air heating load (KJ/hr)
Q_S	maximum solar heating contribution (KJ/hr)
Q_u	useful heat collected by the collector (KJ/hr)
R_b	ratio of beam radiation on tilted surface to horizontal surface
R_e	Reynolds Number
s	collector slope
S_c	solar constant
T_1, T_2	temperature of upper and lower plates of the air channel (°C)
T_a	ambient temperature (°C)
T_{ave}	average temperature that collector losses heat from (°C)
T_{bg}	temperature of building or process (°C)
T_{fi}	collector fluid inlet temperature (°C)
T_{fm}	average collector fluid temperature (°C)
T_{fo}	collector fluid outlet temperature (°C)
T_{in}	inlet temperature to the building (°C)
T_{plate}	average temperature of the collector absorber plate (°C)
U_L	collector heat loss coefficient (W/(m² °C)
U_0	total plate to fluid heat transfer coefficient (W/(m² °C)
x	matrix constant
y	matrix constant

α	solar absorptivity	ρ	density (kg/m³)
δ	solar declination	σ	Stefan-Boltzmann constant
γ	azimuth angle	ω	hour angle
ϕ	latitude	$\tau\alpha$	transmission-absorption product
π	3.14159	$(\tau\alpha)_e$	effective transmission-absorption product
μ	absolute viscosity		